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Modelling the impacts of climate change and crop management on phenological trends of spring and winter wheat in China

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ABSTRACT

Crop phenology is co-determined by climate change and crop management. Over recent decades, climate change-related alterations in crop phenology have been observed and reported for various global crops. However, attributing changes in crop phenology to climate change is difficult, because there have been concurrent changes in crop management. In this paper, we isolated and quantified the impacts of climate change and crop management on the changes of wheat phenology in China, during the period 1981–2010, using a first-difference multiple regression model. Our results shows: (1) based on observed phenological data, in spring/winter wheat, the mean sowing and emergence date were delayed by 0.91/2.29 and 0.39/0.73 days decade^{-1}; mean anthesis and maturity date advanced by 1.05/2.28 and 0.01/1.42 days decade^{-1}; mean length of vegetative growth period (VGP) and whole growth period (WGP) were shortened by 1.09/2.86 and 0.89/3.69 days decade^{-1}; mean length of reproductive growth period (RGP) was prolonged by 0.55/0.61 days decade^{-1}. (2) At most stations, changing direction of wheat phenology affected by isolated impacts of climate change or crop management was consistent with that affected by combined impacts of climate change and crop management. (3) For observed trends of most phenological stages and growth periods, relative contribution from climate change was smaller than from crop management, and average temperature contributed the most among the three contributors (average temperature, cumulative precipitation, and cumulative sunshine hours) to isolated impacts of climate change on wheat phenology. (4) Crop management over the three decades was shown to have helped reduce the lengths of VGP and WGP, but increase the length of RGP for both spring and winter wheat, implying that shorter-duration varieties with a higher yield or better yield stability in changing climate might have been introduced by farmers.

1. Introduction

The International Panel on Climate Change recently reported that many of the observed changes since the industrial revolution are unprecedented and in the Northern Hemisphere, 1983–2012 was the warmest 30-year period of the last 1400 years (IPCC, 2013). A number of studies have shown that the phenology of wild (Clark et al., 2014; Dai et al., 2014; Gordo and Sanz, 2010) and crop (Anwar et al., 2015; Li et al., 2014) plants has changed in tandem with climate change. Most studies on plants report that as temperature has increased, spring phenology has advanced and autumn phenology has become delayed (Ge et al., 2016; Liu et al., 2016). In recent decades, the earlier flowering and maturity observed in crop plants have been considered to be associated with increasing temperatures (Fujisawa and Kobayashi, 2010; Hu et al., 2005). However, crop phenology is simultaneously affected by crop management (like cultivar shift and sowing date adjustment) and simply attributing crop phenology changes to climate change or even climate warming, is difficult and possibly unjustified (Craufurd and Wheeler, 2009). Various approaches have been used to isolate impacts of climate change from crop management in recent years. One of the most commonly used approaches is crop modelling and has been used for wheat in China (He et al., 2015; Wang et al., 2013; Xiao et al., 2016) and cotton in Pakistan (Ahmad et al., 2017). Another commonly used approach is statistical method, and the key point of this method is to determine the detrended method such as smoothing splines method (Zhang et al., 2013) or moving averages

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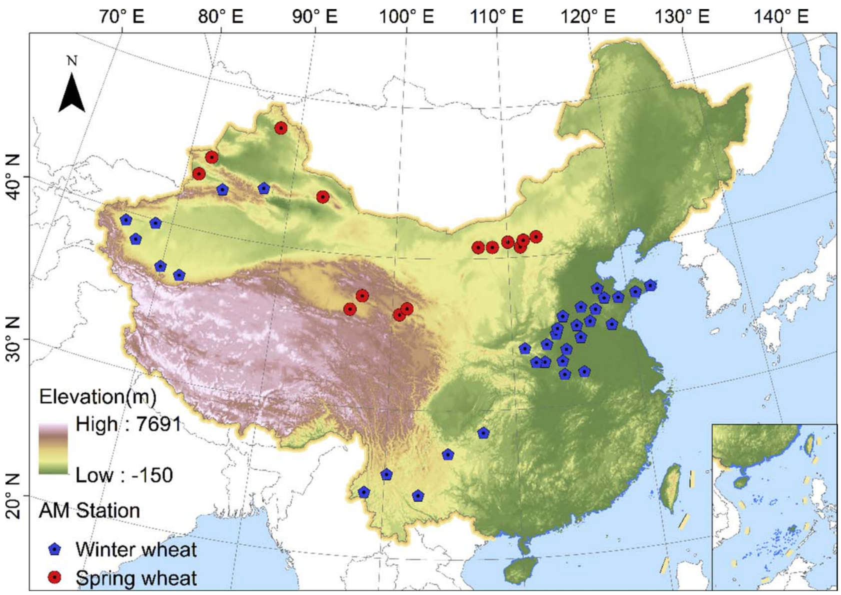

Fig. 1. Spatial distribution of agro-meteorological stations (AM Station).

method (Tao et al., 2013). In addition to these in-silico methods, a field warming experiment was conducted to investigate the responses of soybean phenology to climate warming, using infrared heaters (Zhang et al., 2016).

At the same time, some effective adaptation strategies in response to changing climate have been found and verified during this process. Climate warming accelerated crop growth and shortened the growing periods whereas cultivars shift might prolong the crop growing season, thus adopting cultivars with longer-duration might be an adaptive strategy in responses to warming climate for winter wheat in the North China Plain (Xiao et al., 2013), single rice and early rice in China (Zhang et al., 2013), maize in the U.S. corn belt (Sacks and Kucharik, 2011) and in the North China Plain (Li et al., 2014). Introduction of later-maturing cultivars compensated for the increased temperature effects on wheat phenology, effectively counteracted and even reversed reduction of wheat growth duration due to climate warming (He et al., 2015). Besides, the later-maturity cultivars significantly improved wheat yield and water use efficiency and increasing precipitation during the longer duration of later-maturity cultivars partially compensated for wheat evapotranspiration (Ding et al., 2016). Particularly, for other crops, a shorter-duration cultivars could be an effective choice for adapting climate change as it was reported that earlier anthesis or heading date could avoid extreme heat stress (Nagarajan et al., 2010) and reduce the exposure to drought (Jagadish et al., 2012) during grain-filling period, which would consequently benefit yield. In China, a shorter-duration cultivars for late rice have been introduced by farmers (Tao et al., 2013) and in German, oat with shorter-duration cultivars were advocated in response to climate warming (Siebert and Ewert, 2012). In addition to selecting varieties with appropriate maturation times to mitigate against effects of climate warming on crop yield, adjusting the sowing date may provide an additional option as earlier sowing dates were able to lower the increased trend in average temperature during growing period of spring wheat and then prolonged growing season length as well as potentially benefited productivity (Xiao et al., 2016). In Northeast China, Zhao et al. (2015) found that farmers have taken advantage of the increasing temperatures by adjusting maize sowing dates and alternating cultivars, which prolonged growing season and increased grain yield for spring maize during 1981–2007. Particularly, increasing grain yield from advancing sowing date (1.1–7.3%) was far less than that from introducing later-maturity cultivars (6.5–43.7%) (Zhao et al., 2015).

While a majority of research has reported that increases in temperature have resulted in accelerated crop growth and shortened growing seasons (Wang et al., 2013; Zhang et al., 2013), responses of crop phenology and yield to other functions of climate change, such as precipitation and sunshine hours, and options for crop management and crop breeding have rarely been reported. Quantifying the contribution of these factors to crop phenology and yield would benefit farmers' decision-making on appropriate climate change mitigation strategies to facilitate sustainable agriculture (Anwar et al., 2015; Sacks and Kucharik, 2011).

In this study, we compiled a wheat phenological dataset from 48 agro-meteorology stations in China, covering the period 1981–2010, in order to (1) isolate and quantify impacts of climate change and crop management on changes of wheat phenology; (2) compare relative contribution of climate change and crop management on observed changes of wheat phenology; (3) and further discuss relative contribution of average temperature, cumulative precipitation and cumulative sunshine hours on changes of wheat phenology only affected by climate change.

2. Material and methods

2.1. Agro-meteorological stations and data

The data for wheat phenology in China covering the period of 1981–2010 were collected at 48 agro-meteorological stations operated by the China Meteorological Administration and provincial meteorological administration (Fig. 1). Phenological data include dates of four key phenological stages which are sowing, emergence, anthesis and maturity; phenological data also contain other crop management records, such as cultivars, irrigation and fertilization practices. With these data, lengths during vegetative growth period (VGP, from emergence to anthesis), reproductive growth period (RGP, from anthesis to maturity) and whole growth period (WGP, from sowing to maturity) for every year at each station were calculated. In the study period, the average level of growth situation, climate condition and crop management for spring and winter wheat cropping system was presented in Tables 1 and 2. According to cultivar records, we found that wheat cultivar was shifted approximately every 2–3 years. Therefore, the observations of wheat phenology can be treated as a result of combined impacts of historical climate change and crop management adjustments (especially cultivar shifts). The matched daily weather data, including mean temperature, precipitation and sunshine hours from 1981 to 2011, were downloaded from the China Meteorological Data Website (http://data.cma.cn/site/index.html) operated by the China Meteorological Administration.

Table 1
Summary of mean and standard deviation for date of phenological stages, length of growth periods and climatic factors during corresponding periods in each wheat cropping system.

Cropping System	Phenology	[b]Date (DOY) (or Length (day))	[b]T_{mean} (°C)	[b]PRE (mm)	[b]SSD (h)
Spring Wheat ([a]14)	SD	96 ± 7	4.71 ± 1.65	12.50 ± 10.57	258.18 ± 23.66
	ED	116 ± 6	9.19 ± 1.55	17.33 ± 13.20	269.46 ± 24.51
	AD	183 ± 5	19.39 ± 1.13	51.74 ± 25.89	280.81 ± 27.80
	MD	220 ± 7	19.31 ± 1.03	55.13 ± 26.87	280.35 ± 26.27
	VGP	67 ± 6	14.80 ± 0.87	121.65 ± 39.53	925.29 ± 57.77
	RGP	37 ± 5	19.40 ± 0.90	110.54 ± 40.29	582.20 ± 43.53
	WGP	124 ± 9	14.38 ± 0.78	185.13 ± 52.14	1393.02 ± 73.81
Winter Wheat ([a]34)	SD	284 ± 7	15.38 ± 1.15	38.22 ± 33.13	186.49 ± 31.66
	ED	294 ± 7	14.32 ± 1.19	33.78 ± 29.88	186.15 ± 31.66
	AD	118 ± 5	17.62 ± 1.14	42.60 ± 27.83	223.35 ± 29.67
	MD	154 ± 5	22.59 ± 1.14	66.44 ± 41.46	223.87 ± 31.25
	VGP	202 ± 8	7.90 ± 0.76	161.29 ± 53.50	1289.35 ± 108.71
	RGP	34 ± 4	20.12 ± 0.93	115.08 ± 52.33	479.02 ± 50.82
	WGP	246 ± 8	9.94 ± 0.72	244.80 ± 73.38	1571.96 ± 125.42

Notes: SD: sowing date; ED: emergence date; AD: anthesis date; MD: maturity date; VGP: duration from emergence to anthesis; RGP: duration from anthesis to maturity; WGP: duration from sowing to maturity; T_{mean}: average temperature; PRE: cumulative precipitation; SSD: cumulative sunshine hours.
[a] number of stations.
[b] mean ± standard deviation.

Table 2
Summary of mean and standard deviation for the changing times of wheat varieties as well as total irrigation amount and total nitrogen amount during the whole growth period in each cropping system.

Cropping System	[b]Changing Times	[b]Irrigation (mm)	[b]Nitrogen (kg ha^{-1})
Spring Wheat ([a]14)	14 ± 6	195.89 ± 73.09	104.47 ± 79.87
Winter Wheat ([a]34)	16 ± 6	128.84 ± 63.40	172.62 ± 96.38

[a] number of stations.
[b] mean ± standard deviation.

2.2. Analysis methods

2.2.1. Calculate historical trends of observed climate and wheat phenology

Trends of observed wheat phenology and climatic factors (average temperature, cumulative precipitation and cumulative sunshine hours) during corresponding periods can be calculated using linear regression model with the year as independent variable. The corresponding period is determined by the month of mean onset of the phenological event at each station (Zhang et al., 2013). For example, the corresponding period of a phenological stage like sowing date, is the month of mean onset of sowing date in the past at the station; and the corresponding period of a growth period like period from sowing to maturity, is the period from the month of mean onset of sowing date to the month of mean onset of maturity date in the past at the station. By holding the constant corresponding period of a specific phenological stage or growth period every year at the same station, the calculated trends of average temperature, cumulative precipitation and cumulative sunshine hours are independent from the phenology changes (Ahmad et al., 2017; He et al., 2015). For each station, the trend of average temperature, cumulative precipitation and cumulative sunshine hours of the corresponding period was calculated as Eq. (1):

$$Cli = T_{cli} \times Year + B_{cli} \tag{1}$$

In Eq. (1), *Cli* represents observed average temperature (°C), cumulative precipitation (mm) or cumulative sunshine hours (h) of the corresponding period; *Year* represents the year; B_{cli} represents the intercept of the regression model; T_{cli} represents the slope of the regression model, which is the trend of the climatic factor.

For each station, the trend of observed phenological stage or growth period length was calculated as Eq. (2):

$$Phe = T_{phe} \times Year + B_{phe} \tag{2}$$

In Eq. (2), *Phe* represents observed phenological stage (DOY) or growth period length (days); *Year* represents the year; B_{phe} represents the intercept of the regression model; T_{phe} represents the slope of the regression model, that is the observed trend of the phenological stage or growth period length (days a^{-1}). The regression coefficient (T_{phe}) reflects the combined impacts of climate change and crop management on wheat phenology.

2.2.2. Isolate impacts of climate change and crop management on trends of wheat phenology

The first-difference method is a common de-trending technique to establish climate-yield relationships because it can reduce the influence of long term trends due to technological improvements or other effects caused by adjustments from crop practices (Lobell et al., 2005; Veron et al., 2015; Zhang and Huang, 2013). The first-difference value is the absolut difference ($\Delta Y = Y_{t+1} - Y_t$) between two consecutive years (year t and year ($t + 1$)), referring to year-to-year changes in yield or other things we study. Here we used the first-difference method to establish relationships between climate and phenology. To differentiate isolated impacts of climate change from the combined effects of climate change and crop management on changes of wheat phenology, first-difference values of observed time series data of wheat phenology and climate were calculated and subsequently used in a regression model to estimate responses of wheat phenology to key climatic factors. The established multiple regression model was shown as Eq. (3):

$$\Delta Phe = S_{tem} \times \Delta Tem + S_{pre} \times \Delta Pre + S_{ssd} \times \Delta Ssd + int \tag{3}$$

In Eq. (3), ΔPhe represents the first-difference value of the phenological stage or growth period length; ΔTem, ΔPre and ΔSsd represents the first-difference value of average temperature, cumulative precipitation and cumulative sunshine hours of the corresponding period, respectively; *int* represents the intercept of the regression model; S_{tem}, S_{pre} and S_{ssd} represents the sensitivity of wheat phenology to temperature (days $°C^{-1}$), precipitation (days mm^{-1}) and sunshine hours (days h^{-1}), respectively.

Therefore, the trend of wheat phenology just affected by climate change was calculated as Eq. (4):

$$T_{phe\,cli} = S_{tem} \times T_{tem} + S_{pre} \times T_{pre} + S_{ssd} \times T_{ssd} \tag{4}$$

In Eq. (4), T_{phe_cli} represents the trend of phenological stage or growth period length (day a^{-1}) under the isolated impacts of climate change; T_{tem}, T_{pre} and T_{ssd} represents the trend of average temperature, cumulative precipitation and cumulative sunshine hours of the corresponding period, respectively; and other parameters are defined the same as those in Eq. (3).

Isolated impacts of crop management on wheat phenology were obtained indirectly after eliminating the impacts of climate change from the combined effects of climate change and crop management, which was calculated as Eq. (5):

$$T_{phe\,man} = T_{phe} - T_{phe\,cli} \tag{5}$$

In Eq. (5), T_{phe_man} represents the trend of phenological stage or growth period length (days a^{-1}) under the isolated impacts of crop management. The statistical test for difference of their mean of T_{phe} and T_{phe_cli} is conducted by a two-sample *t*-test at all stations grouped by wheat-cropping system, and the result "$P < 0.05$" indicates T_{phe_man} is significant statistically.

2.2.3. Calculate relative contribution of each influencer on trends of wheat phenology

According to Eq. (4) in Section 2.2.2, the trend of wheat phenology under isolated impacts of climate change depends on effects from temperature, precipitation and sunshine hours. For example, relative contribution from changes of average temperature (RC_{tem}) on wheat phenology was calculated as Eq. (6):

$$RC_{tem} = \frac{S_{tem} \times T_{tem}}{|S_{tem} \times T_{tem}| + |S_{pre} \times T_{pre}| + |S_{ssd} \times T_{ssd}|} \times 100\% \tag{6}$$

Other parameters are defined the same as those in Eq. (4). Similarly, relative contribution from changes of cumulative precipitation or cumulative sunshine hours on wheat phenology can be calculated in the same way, which is written as RC_{pre} and RC_{ssd}, respectively. For a specific phenological stage or growth period length, the average relative contribution from changes of average temperature ($\overline{RC}_{tem}$) for spring wheat or winter wheat was calculated as Eq. (7):

$$\overline{RC}_{tem} = \frac{\sum_{i=1}^{n} RC_{tem,i}}{\left|\sum_{i=1}^{n} RC_{tem,i}\right| + \left|\sum_{i=1}^{n} RC_{pre,i}\right| + \left|\sum_{i=1}^{n} RC_{ssd,i}\right|} \times 100\% \tag{7}$$

In Eq. (7), n represents station number in each wheat-cropping system; $RC_{tem,i}$, $RC_{pre,i}$ and $RC_{ssd,i}$ represents relative contribution from changes of average temperature, cumulative precipitation and cumulative sunshine hours at station i, respectively. Similarly, the average relative contribution from cumulative precipitation or cumulative sunshine hours for each wheat-cropping system can be calculated in the same way, which was written as $\overline{RC}_{pre}$ and $\overline{RC}_{ssd}$.Besides, Eq. (5) in Section 2.2.2 indicates that the observed trend of wheat phenology is affected by combined effects of climate change and crop management. Particularly, relative contribution from climate change (RC_{cli}) on a specific phenological stage or growth period length at each station was calculated as Eq. (8):

$$RC_{cli} = \frac{T_{phe\,cli}}{|T_{phe\,cli}| + |T_{phe\,man}|} \times 100\% \tag{8}$$

Other parameters are defined the same as those in Eq. (8). Likewise, relative contribution from crop management can be calculated in the same way, which is written as RC_{man}. For a specific phenological stage or growth period length, the average relative contribution from climate change ($\overline{RC}_{cli}$) for spring wheat or winter wheat was calculated as Eq. (9):

$$\overline{RC}_{cli} = \frac{\sum_{i=1}^{n} RC_{cli,i}}{\left|\sum_{i=1}^{n} RC_{cli,i}\right| + \left|\sum_{i=1}^{n} RC_{man,i}\right|} \times 100\% \tag{9}$$

In Eq. (9), n represents the station number in each wheat-cropping system; $RC_{cli,i}$ and $RC_{man,i}$ represents relative contribution from climate change or crop management at station i. Likewise, the average relative contribution from crop management for each wheat-cropping system can be calculated in the same way, which was written as $\overline{RC}_{man}$.

Table 3
Mean trends of temperature (T_{tem}), precipitation (T_{pre}) and sunshine hours (T_{ssd}) per decade during corresponding periods for spring and winter wheat cropping systems.

Cropping System	Phenology	[b]T_{tem} (°C decade^{-1})	[b]T_{pre} (mm decade^{-1})	[b]T_{ssd} (h decade^{-1})
Spring wheat ([a]14)	SD	0.55	1.56	−1.90
	ED	0.51	1.18	−0.96
	AD	0.64	−0.80	−3.09
	MD	0.48	−0.24	−5.28
	VGP	0.51	1.33	−6.74
	RGP	0.56	−0.55	−8.63
	WGP	0.52	2.19	−12.83
Winter Wheat ([a]34)	SD	0.48	−5.29	−5.77
	ED	0.46	−4.46	−4.47
	AD	0.46	2.40	1.01
	MD	0.45	0.08	−4.51
	VGP	0.50	−2.19	−9.06
	RGP	0.46	2.04	−2.95
	WGP	0.50	−3.98	−14.81

Note: SD: sowing date; ED: emergence date; AD: anthesis date; Notes: MD: maturity date; VGP: duration from emergence to anthesis; RGP: duration from anthesis to maturity; WGP: duration from sowing to maturity.
[a] number of stations.
[b] mean of trends.

3. Results

3.1. Climate trends

The historical mean trends of average temperature, cumulative precipitation and cumulative sunshine hours of the corresponding period of phenological stages and growth periods of spring and winter wheat are shown in Table 3. On average, there was a general trend towards warming for spring and winter wheat for all corresponding periods of sowing, emergence, anthesis, maturity, VGP, RGP and WGP. The rates of increase in average temperature for all corresponding periods for spring wheat were higher than those for winter wheat.

Trends of cumulative precipitation differed significantly across corresponding periods of phenological stages and growing periods. On average, cumulative precipitation tended to increase during corresponding periods of sowing, emergence, VGP and WGP and a decreasing trend occurred to corresponding periods of anthesis, maturity and RGP for spring wheat. On the contrary, cumulative precipitation decreased during corresponding periods of sowing, emergence, VGP and WGP and increased during corresponding periods of anthesis, maturity and RGP for winter wheat. Both the greatest increasing trend and the greatest decreasing trend were found in winter wheat: the former occurred during the corresponding period of anthesis with a rate of 2.40 mm decade^{-1}, while the latter occurred during the corresponding period of sowing with a rate of −5.29 mm decade^{-1}.

With the exception of anthesis for winter wheat, there was a decrease in cumulative sunshine hours for all corresponding periods of sowing, emergence, anthesis, maturity, VGP, RGP and WGP for spring and winter wheat. The cumulative sunshine hours decreased in the similar rate during the period of WGP for each cropping system: the decreasing rate was 12.83 h decade^{-1} for spring wheat and 14.81 h decade^{-1} for winter wheat.

3.2. Differences of sensitivity of wheat phenology to various climatic factors

Sensitivities of wheat phenological stages (sowing, emergence, anthesis and maturity) and growth periods (VGP, RGP and WGP) to climatic factors (average temperature, cumulative precipitation and cumulative sunshine hours) for spring and winter wheat using detrended data are shown in Fig. 2. On average, dates of sowing, emergence,

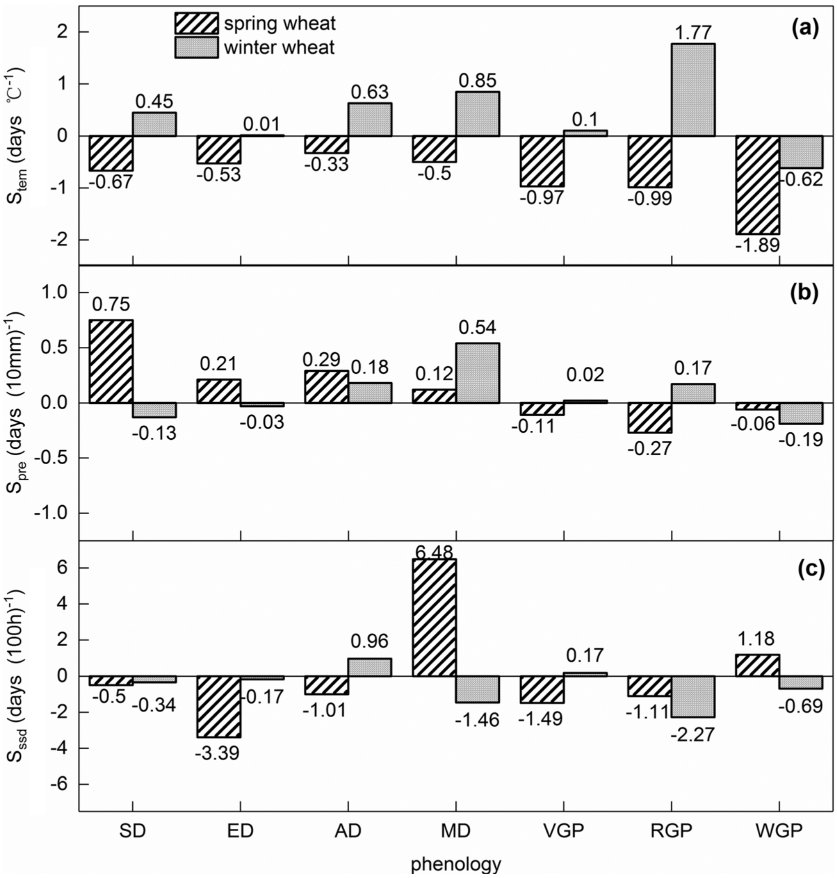

Fig. 2. Sensitivity of wheat phenology to climatic factors for spring and winter wheat cropping systems using detrended data. Values denote the mean of sensitivity of all stations in each wheat-cropping system. SD: sowing date; ED: emergence date; AD: anthesis date; MD: maturity date; VGP: duration from emergence to anthesis; RGP: duration from anthesis to maturity; WGP: duration from sowing to maturity.

anthesis and maturity and lengths of VGP, RGP and WGP were all negative to average temperature during the corresponding periods for spring wheat. In contract, dates of sowing, emergence, anthesis and maturity and lengths of VGP and RGP were all positive to average temperature during the corresponding periods for winter wheat except that the length of WGP was negative to average temperature during the corresponding period. On average, dates of the four phenological stages were all positive to cumulative precipitation while lengths of the three growth periods were all negative to cumulative precipitation during the corresponding periods for spring wheat.

Overall, phenological stages differed in their degrees of sensitivity to average temperature, cumulative precipitation and cumulative sunshine hours for spring wheat: sowing date was most sensitive to average temperature and cumulative precipitation, while maturity date was most sensitive to cumulative sunshine hours. Nevertheless, maturity date was always the most sensitive phenological stage responding to average temperature, cumulative precipitation and cumulative sunshine hours for winter wheat. Furthermore, for spring wheat, VGP and RGP had similar sensitivity to average temperature and cumulative sunshine hours, whereas RGP was more sensitive to cumulative precipitation than VGP. For winter wheat, RGP was more sensitive to average temperature (and cumulative precipitation and cumulative sunshine hours) than VGP. On average, the length of WGP for spring wheat was shortened by average temperature and cumulative precipitation but extended by cumulative sunshine hours, whereas the length of WGP for winter wheat was shortened by average temperature, cumulative precipitation and cumulative sunshine hours.

3.3. Impacts of climate change and crop management on wheat phenology

Fig. 3 illustrates historical trends of dates of four phenological stages (sowing, emergence, anthesis and maturity) and lengths of three growth periods (VGP, RGP and WGP) under the combined and isolated impacts of climate change and crop management at each station. According to Fig. 3, variation range of trends at stations under isolated impacts of climate change were narrower than those under isolated impacts of crop management or combined impacts. In addition, the median of trends under the isolated impacts of crop management was similar to that under the combined impacts. Across combined and isolated impacts of climate change and crop management, sowing date and emergence date at most stations were delayed; anthesis date and maturity date at most stations advanced; the length of VGP and WGP at most stations shortened; and the length of RGP at most stations prolonged.

The means of trends of each phenological stage or growth period at stations grouped by wheat-cropping system are summarized in Table 4. Under the combined impacts of climate change and crop management, the directions of trends for spring wheat and winter wheat were consistent, nevertheless rates of trends for spring wheat were smaller than those for winter wheat. For spring wheat, the isolated impacts of climate change advanced sowing, emergence and anthesis dates, delayed maturity date, and shortened VGP, RGP and WGP. For winter wheat, the isolated impacts of climate change delayed sowing, emergence, anthesis and maturity dates, shortened VGP and WGP, and prolonged RGP. Trends of phenology under the isolated impacts of crop management were similar to those under the combined effects of climate change and crop management. For both spring wheat and winter wheat, crop management delayed sowing and emergence dates, but advanced anthesis and maturity dates. Crop management shortened VGP and prolonged RGP for both spring and winter wheat, however, WGP was prolonged for spring wheat and shortened for winter wheat. There were some differences in the combined effects of climate change and management compared with the effect of climate change in isolation on wheat phenology (Table 4). Combined climate change and management

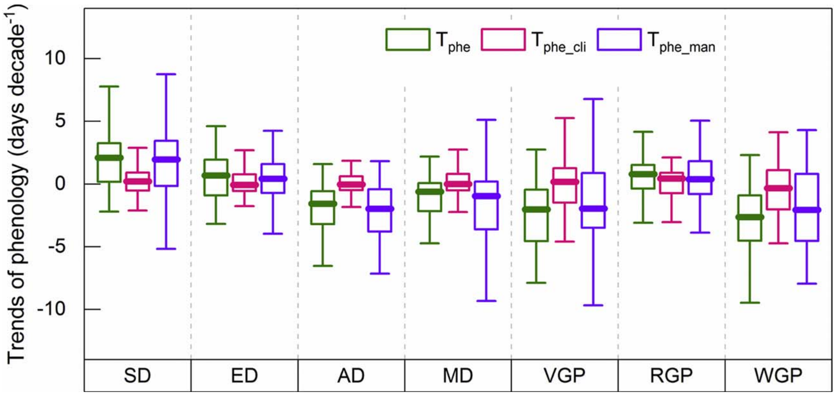

Fig. 3. Trends of wheat phenology at each station based on observed and detrended data. T_{phe} denotes combined impacts of climate change and crop management on wheat phenology; T_{phe_cli} denotes isolated impacts of climate change on wheat phenology; T_{phe_man} denotes isolated impacts of crop management on wheat phenology. SD: sowing date; ED: emergence date; AD: anthesis date; MD: maturity date; VGP: duration from emergence to anthesis; RGP: duration from anthesis to maturity; WGP: duration from sowing to maturity.

Table 4

Comparison of trends (days decade^{-1}) of wheat phenology under the effects of climate change and crop management, climate change, and, crop management for spring and winter wheat cropping systems.

Cropping System	Phenology	$^{b}T_{phe}$	$^{b}T_{phe\_cli}$	$^{b}T_{phe\_man}$	t-Test (*p*-value)
Spring Wheat ([a]14)	SD	0.91	−0.11	1.01	0.381
	ED	0.39	−0.38	0.77	0.212
	AD	−1.05	−0.44	−0.61	0.273
	MD	−0.01	0.01	−0.02	0.982
	VGP	−1.09	−0.55	−0.54	0.253
	RGP	0.55	−0.34	0.89	0.296
	WGP	−0.89	−1.19	0.30	0.773
Winter Wheat ([a]34)	SD	2.29	0.29	2.00	0.000**
	ED	0.73	0.42	0.31	0.519
	AD	−2.28	0.23	−2.52	0.000**
	MD	−1.42	0.35	−1.77	0.000**
	VGP	−2.86	−0.29	−2.58	0.001**
	RGP	0.61	0.43	0.18	0.623
	WGP	−3.69	−0.06	−3.62	0.002**

Notes: SD: sowing date; ED: emergence date; AD: anthesis date; MD: maturity date; VGP: duration from emergence to anthesis; RGP: duration from anthesis to maturity; WGP: duration from sowing to maturity. Note that p-value is the result of two-sample t-test performed on trends under combined effects (T_{phe}) and trends under isolated effects of climate change (T_{phe_cli}).

[a]number of stations.

[b]mean of trends.

*significant at 0.05 probability level.

**significant at 0.01 probability level.

effects and isolated climate change effects were significantly different ($p < 0.05$) for sowing, anthesis and maturity dates and for VGP and RGP in winter wheat. On the other hand, trends under combined effects were closed to those under isolated effects of climate change for WGP for spring wheat ($T_{phe} = -0.89$ days decade^{-1}, $T_{phe\_cli} = -1.19$ days decade^{-1}) and RGP for winter wheat ($T_{phe} = 0.61$ days decade^{-1}, $T_{phe\_cli} = 0.43$ days decade^{-1}).

4. Discussion

4.1. Comparison of impacts of climate change and crop management

The relative impacts on crop phenology of climate change and crop management in spring and winter wheat cropping systems are shown in Fig. 4. The plus or minus symbol of percentage indicates the changing direction of crop phenology caused by climate change or crop management. Under combined effects of climate change and crop management for spring and winter wheat, dates of sowing and emergence was delayed; dates of anthesis and maturity was advanced; length of VGP and WGP was shortened; and, length of RGP was prolonged. This finding was consistent with the earlier studies of wheat in other regions (Hu et al., 2005; Tao et al., 2012, 2014; Xiao et al., 2015). Similarly, earlier onset of anthesis date and maturity date have been found for other agricultural crops (Craufurd and Wheeler, 2009; Fujisawa and Kobayashi, 2010; Siebert and Ewert, 2012).

Particularly, relative contribution of climate change and crop management to changes in wheat phenology varied across phenological stages and growth periods. Our results show that crop management contributed more than climate change to changes in sowing date and emergence date for both spring wheat and winter wheat (Fig. 4). Earlier studies have reported that farming management decisions could alter sowing date in response to changes in climate (Estrella et al., 2007). The onset of emergence date depends on sowing date and later sowing date could reduce the shortening of season lengths and predicted yield losses of wheat in warming climate conditions (Lobell et al., 2012). It is likely that the delay of sowing date and emergence date in the past three decades was a response of farmers to climate change. In our study, the key driving factor for the advancement of anthesis date and maturity date was climate change for spring wheat, and crop management for winter wheat. However, Xiao et al. (2013) discovered that isolated effects of climate change would advance anthesis date and maturity date for winter wheat, and the modelling advanced trends were even larger than observed trends, which meant that climate change dominated trends of anthesis date and maturity date. In a recent published paper, Xiao et al. (2016) performed a more in-depth study to model the impacts of climate change, sowing date adjustment and cultivar shift on spring wheat phenology with ASPIM model. Our findings concur with Xiao et al. (2016), as they also found that under isolated effects of climate change, anthesis date and maturity date for spring wheat would advance, with climate change predicted to contribute more than crop management at most stations. In addition, Xiao et al. (2016) discovered that crop management (especially sowing date adjustment) resulted in a greater rate of trends of VGP and WGP while climate change generated a larger rate of trend of RGP. This phenomenon was consistent with our results for winter wheat but contrary to our results for spring wheat. According to Fig. 4, reduction of length of VGP and WGP was mainly due to climate change for spring wheat but crop management for winter wheat; and extension of length RGP was mainly resulted from crop management for spring wheat but climate change for winter wheat. This inconformity of results between our study and earlier reports might be partly due to the different study method. In our study, we used a statistical model based on observed data, and this had the advantage that data were empirical; however, there is a potential, albeit difficult to verify, assumption that consecutive years have consistent crop management. Crop modelling can simulate crop phenology under specific circumstances, but the simulated results are uncertain and depends on the simulated accuracy and calibration precision of crop model.

We also found that crop management was important in reducing the lengths of VGP and WGP, but increasing the lengths of RGP for both spring wheat and winter wheat. This finding implied that the shorter-duration cultivars were planted in response to climate change to some extent. Indeed, a similar strategy of introducing new cultivar adapted to

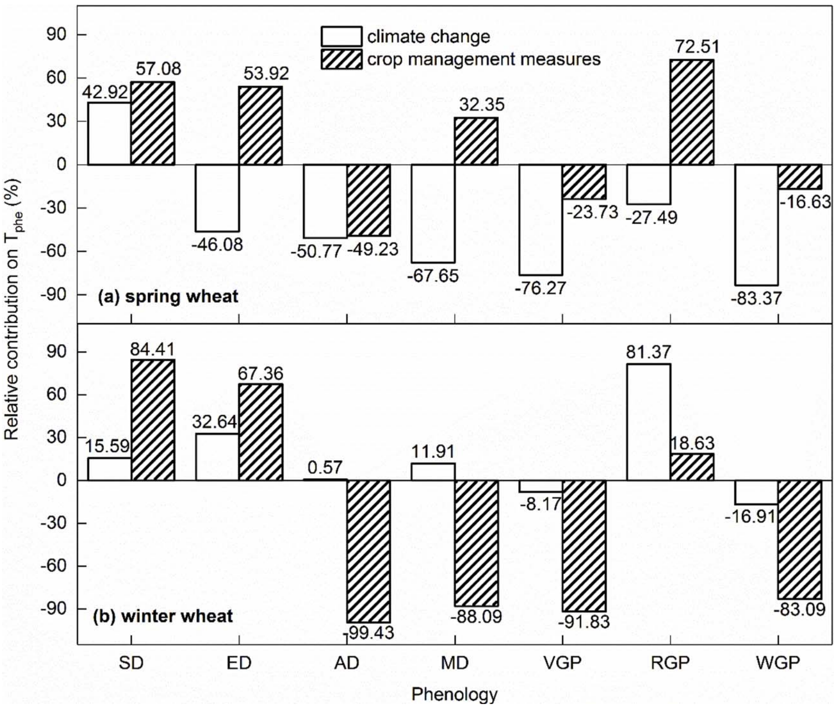

Fig. 4. Average relative contribution of climate change and crop management on T_{phe} for spring wheat (a) and winter wheat (b). Values denotes the mean of percentage of all stations in each wheat-cropping system. SD: sowing date; ED: emergence date; AD: anthesis date; MD: maturity date; VGP: duration from emergence to anthesis; RGP: duration from anthesis to maturity; WGP: duration from sowing to maturity.

ongoing climate change has been reported for wheat (Tao et al., 2012; Xiao et al., 2015), maize (Li et al., 2014; Sacks and Kucharik, 2011), rice (Tao et al., 2013) and oat (Siebert and Ewert, 2012). In northeast China, however, most farmers had adopted longer-duration maize cultivars because the increase in temperature provided better conditions for growth and production (Li et al., 2014). Likewise, an introduction of longer-duration (or later-maturity) cultivars could be found for winter wheat in the Loess Plateau of China (Ding et al., 2016). It seems to be widely accepted that a shorter-duration cultivar is likely to result in yield reductions because there is less time for biomass accumulation during the vegetative phase. Despite the possible yield loss, using a shorter-duration cultivar could be a positive strategy for adapting climate change since the warmer climate would accelerate the growth of cycle. In fact, whether crop yield would be lost or not mainly depends on the duration of the grain-filling period rather than the whole growing season. The shorter-duration cultivars have been advocated for oat in German in response to climate warming (Sacks and Kucharik, 2011). In China, it was detected that short-duration cultivars for late rice and long-duration cultivars for single and early rice were planted for adapting climate warming (Zhang et al., 2013). And there is also reported that the harmful influence of the thermal trend was partly compensated as a result of introducing new cotton cultivars with higher thermal time requirements in Pakistan (Ahmad et al., 2017). The introduction of heat-tolerant and drought-resistant varieties in most areas of Jiangsu province could mitigate the influences of climate change on winter wheat production and ensure high and stable yields (Tao et al., 2016). Thus, cultivars with higher thermal time requirement and higher temperature tolerance rather than longer or shorter durations seem to be more competitive when growing in warming climate conditions.

4.2. Comparison of impacts of temperature, precipitation and sunshine hours

We found that the relative contribution of each climate factor to phenological changes varied across phenological stages and growing periods (Fig. 5) due to the different sensitivity of phenology to climate factors (Fig. 2) and different trends of climate factors during various corresponding periods (Table 3). Among the three climatic factors, we found that the impacts of average temperature was greatest (> 50%) for most phenological stages and growing periods. As such, our results support the focus on impacts of temperature changes as the main driver of crop phenology changes in earlier studies (Estrella et al., 2007; Li et al., 2014; Wang et al., 2013). Additionally, we also found that cumulative sunshine hours was the greatest contributor to changes in length of VGP for both spring wheat and winter wheat. The impacts of cumulative precipitation on wheat phenology seemed very slight when comparing with the other two climatic factors.

It is widely accepted that increases in temperature can accelerate the onset of anthesis or maturity and then shorten the growing duration (Lobell et al., 2012; Xiao et al., 2013). However, it is unreasonable to simply attribute changes in phenology to climate change since farm management practices have also changed (Craufurd and Wheeler, 2009). Thus, we used a first-difference multiple regression model to isolate impacts of farm management practices, in order to investigate responses of spring and winter wheat phenology to average temperature, cumulative precipitation and cumulative sunshine hours. Our results indicated that, on average, increasing temperature would reduce the duration of WGP for both spring wheat and winter wheat (Fig. 2). Similar findings that climate warming is predicted to accelerate crop growth and shorten the growing season length, have been reported in earlier studies, based on a statistical method (Zhang et al., 2013), crop model (Xiao et al., 2016), and field warming experiment (Zhang et al., 2016). Zhang et al. (2016) discovered that 0.4 °C and 0.7 °C increases in soybean canopy air and soil temperature advanced anthesis date by 3.8 days and shortened growing season length by 4.5 days and Ahmad et al. (2017) found that sowing to maturity duration reduced by 1.97 days $°C^{-1}$ in cotton. Our results also indicate that sowing, emergence, anthesis and maturity dates for winter wheat was positively correlated with average temperature (Fig. 2). That sowing date and emergence date was delayed accompany with increasing temperature might be suggest an auto-adaptive response of winter wheat to the warming trend, as some earlier studies have suggested that too much growth before dormancy could hinder winter wheat survival in the overwintering period (He et al., 2015). However, further research is required to understand why anthesis date and maturity date of winter wheat showed a positive response to increasing temperature.

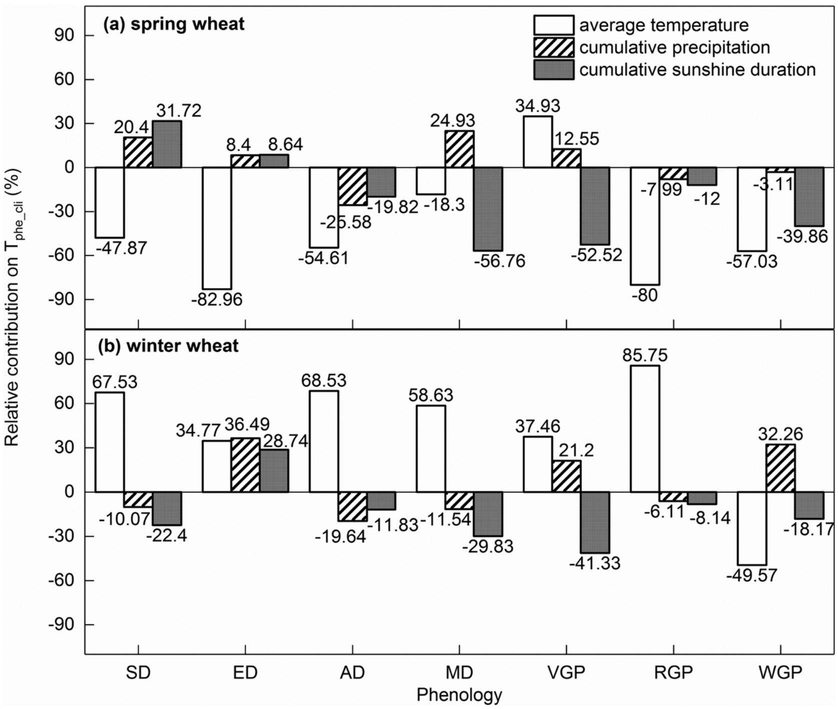

Fig. 5. Average relative contribution of each climatic factor on T_{phe_cli} for spring wheat (a) and winter wheat (b). Values denotes the mean of percentage of all stations in each wheat-cropping system. SD: sowing date; ED: emergence date; AD: anthesis date; MD: maturity date; VGP: duration from emergence to anthesis; RGP: duration from anthesis to maturity; WGP: duration from sowing to maturity.

5. Conclusions

In the past three decades, there was a general increasing trend of temperature as well as a decreasing trend of sunshine hours during wheat growing season in China. At the same time, there were concurrent changes of crop management. Our results demonstrate that the changing direction of wheat phenology affected by the combined and isolated impacts of climate change and crop management were consistent: sowing date and emergence date at most stations tended to be delayed; anthesis date and maturity date at most stations tended to advance; the length of VGP and WGP at most stations were shortened; and the length of RGP at most stations were prolonged. However, the relative contribution of climate change and crop management on changes in wheat phenology were different. Average relative contribution of crop management to changes in dates of sowing and emergence, and length of VGP for spring wheat and changes in dates of sowing, emergence, anthesis and maturity, and length of WGP for winter wheat was greater than that of climate change. Among the three contributors climate change, average temperature contributed the greatest part to changes in dates of sowing, emergence and anthesis, and length of WGP for spring wheat and also dominated changes in dates of sowing, anthesis and maturity, and length of RGP and WGP for winter wheat; and cumulative sunshine hours was the greatest contributor to changes in length of VGP for both spring wheat and winter wheat while impacts of cumulative precipitation on wheat phenology seemed very slight. In addition, we discovered that crop management that wheat producer used in the past helped reduce lengths of VGP and WGP while increase lengths of RGP. We suggested that the shorter-duration wheat varieties with a higher yield or better yield stability in changing climate might have been planted, which could be a viable strategy adapting for climate change.

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References

Ahmad, S., et al., 2017. Quantification of climate warming and crop management impacts on cotton phenology. Plants 6 (1), 7.
Anwar, M.R., et al., 2015. Climate change impacts on phenology and yields of five broadacre crops at four climatologically distinct locations in Australia. Agric. Syst. 132, 133–144.
Clark, J.S., Melillo, J., Mohan, J., Salk, C., 2014. The seasonal timing of warming that controls onset of the growing season. Global Change Biol. 20 (4), 1136–1145.
Craufurd, P.Q., Wheeler, T.R., 2009. Climate change and the flowering time of annual crops. J. Exp. Bot. 60 (9), 2529–2539.
Dai, J., Wang, H., Ge, Q., 2014. The spatial pattern of leaf phenology and its response to climate change in China. Int J. Biometeorol. 58 (4), 521–528.
Ding, D., et al., 2016. Impact assessment of climate change and later-maturing cultivars on winter wheat growth and soil water deficit on the Loess Plateau of China. Clim. Change 138 (1), 157–171.
Estrella, N., Sparks, T.H., Menzel, A., 2007. Trends and temperature response in the phenology of crops in Germany. Global Change Biol. 13 (8), 1737–1747.
Fujisawa, M., Kobayashi, K., 2010. Apple (Malus pumila var. domestica) phenology is advancing due to rising air temperature in northern Japan. Global Change Biol. 16 (10), 2651–2660.
Ge, Q., Dai, J., Cui, H., Wang, H., 2016. Spatiotemporal variability in start and end of growing season in China related to climate variability. Remote Sens. 8 (5), 433.
Gordo, O., Sanz, J.J., 2010. Impact of climate change on plant phenology in mediterranean ecosystems. Global Change Biol. 16 (3), 1082–1106.
He, L., et al., 2015. Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. Agric. For. Meteorol. 200, 135–143.
Hu, Q., Weiss, A., Feng, S., Baenziger, P.S., 2005. Earlier winter wheat heading dates and warmer spring in the U.S. Great Plains. Agric. For. Meteorol. 135 (1–4), 284–290.
IPCC, 2013. Summary for policymakers. In: Stocker, T.F. (Ed.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 3–29.
Jagadish, S.V.K., et al., 2012. Genetic advances in adapting rice to a rapidly changing climate. J. Agron. Crop Sci. 198 (5), 360–373.
Li, Z., et al., 2014. Response of maize phenology to climate warming in Northeast China between 1990 and 2012. Reg. Environ. Change 14 (1), 39–48.
Liu, Q., et al., 2016. Delayed autumn phenology in the Northern Hemisphere is related to change in both climate and spring phenology. Global Change Biol. 22 (11), 3702–3711.
Lobell, D.B., et al., 2005. Analysis of wheat yield and climatic trends in Mexico. Field Crops Res. 94 (2-3), 250–256.
Lobell, D.B., Sibley, A., Ivan Ortiz-Monasterio, J., 2012. Extreme heat effects on wheat senescence in India. Nat. Clim. Change 2 (3), 186–189.
Nagarajan, S., et al., 2010. Local climate affects growth, yield and grain quality of

aromatic and non-aromatic rice in northwestern India. Agric. Ecosyst. Environ. 138 (3–4), 274–281.
Sacks, W.J., Kucharik, C.J., 2011. Crop management and phenology trends in the U. S Corn Belt impacts on yields, evapotranspiration and energy balance. Agric. For. Meteorol. 151 (7), 882–894.
Siebert, S., Ewert, F., 2012. Spatio-temporal patterns of phenological development in Germany in relation to temperature and day length. Agric. For. Meteorol. 152, 44–57.
Tao, F., Zhang, S., Zhang, Z., 2012. Spatiotemporal changes of wheat phenology in China under the effects of temperature, day length and cultivar thermal characteristics. Eur. J. Agron. 43, 201–212.
Tao, F., et al., 2013. Single rice growth period was prolonged by cultivars shifts, but yield was damaged by climate change during 1981–2009 in China, and late rice was just opposite. Global Change Biol. 19 (10), 3200–3209.
Tao, F., et al., 2014. Responses of wheat growth and yield to climate change in different climate zones of China, 1981–2009. Agric. For. Meteorol. 189-190, 91–104.
Tao, S., et al., 2016. Projected crop production under regional climate change using scenario data and modeling: sensitivity to chosen sowing date and cultivar. Sustainability 8 (3), 214.
Veron, S.R., de Abelleyra, D., Lobell, D.B., 2015. Impacts of precipitation and temperature on crop yields in the Pampas. Clim. Change 130 (2), 235–245.
Wang, J., Wang, E., Feng, L., Yin, H., Yu, W., 2013. Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. Field Crops Res. 144, 135–144.
Xiao, D., et al., 2013. Observed changes in winter wheat phenology in the North China Plain for 1981–2009. Int J. Biometeorol. 57 (2), 275–285.
Xiao, D., et al., 2015. Spatiotemporal variability of winter wheat phenology in response to weather and climate variability in China. Mitig. Adapt. Strategies Glob. Chang. 20 (7), 1191–1202.
Xiao, D., Tao, F., Shen, Y., Qi, Y., 2016. Combined impact of climate change, cultivar shift, and sowing date on spring wheat phenology in Northern China. J. Meteorol. Res. 30 (5), 820–831.
Zhang, T., Huang, Y., 2013. Estimating the impacts of warming trends on wheat and maize in China from 1980 to 2008 based on county level data. Int J. Climatol. 33 (3), 699–708.
Zhang, T., Huang, Y., Yang, X., 2013. Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice. Glob. Change Biol. 19 (2), 563–570.
Zhang, L., Zhu, L., Yu, M., Zhong, M., 2016. Warming decreases photosynthates and yield of soybean [Glycine max (L.) Merrill] in the North China Plain. Crop J. 4 (2), 139–146.
Zhao, J., Yang, X., Dai, S., Lv, S., Wang, J., 2015. Increased utilization of lengthening growing season and warming temperatures by adjusting sowing dates and cultivar selection for spring maize in Northeast China. Eur. J. Agron. 67, 12–19.